Future Measurement of the Neutrino Mixing Parameter U_{e3} at Nuclear Reactors

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Physics Motivation

- The evidence for neutrino mass is quite strong.

- Massive neutrinos oscillate between flavors. This oscillation is governed by the MNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

which relates the mass eigenstates to the flavor eigenstates.

- U_{e3} is the only element yet to be measured

<0.2 (CHOOZ & Palo Verde)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sim 0.7 & \sim 0.7 & \sin\theta_{13}e^{i\delta} \\ \sim -0.5 & \sim 0.5 & \sim 0.7 \\ \sim 0.5 & \sim -0.5 & \sim 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- This component is important because it sets the scale for CP violation in the lepton sector.
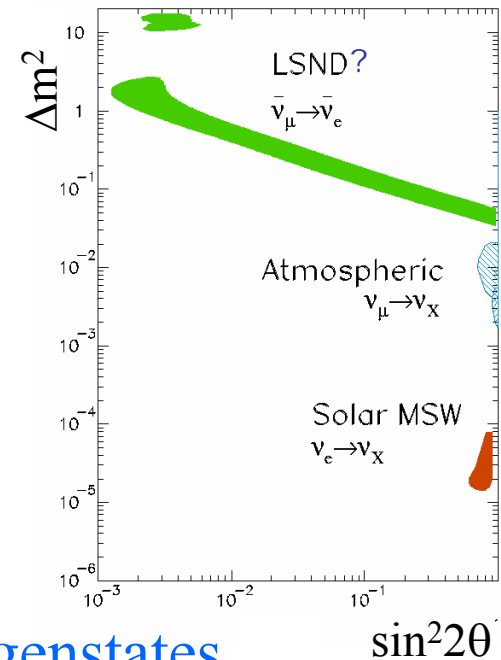
Physics Motivation (continued)

• To simplify, consider oscillations involving just two neutrinos, then the oscillation probability is just

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2 2\theta}_{\text{Amplitude}} \underbrace{\sin^2(1.27\Delta m^2 L / E_\nu)}_{\text{Frequency}}$$

where L is the distance traveled by the neutrino, E_ν is the neutrino energy, and Δm^2 is the difference of mass squares for of the underlying mass eigenstates.

• Δm_{13}^2 is known from atmospheric ($\Delta m_{13}^2 = \Delta m_{23}^2 + \Delta m_{12}^2 \approx \Delta m_{23}^2$)

Atmospheric   Solar

If know your neutrino energy you know where to put your detector to optimize oscillations.

Method of Measuring sin²2θ₁₃

1. **Measure with an Accelerator**
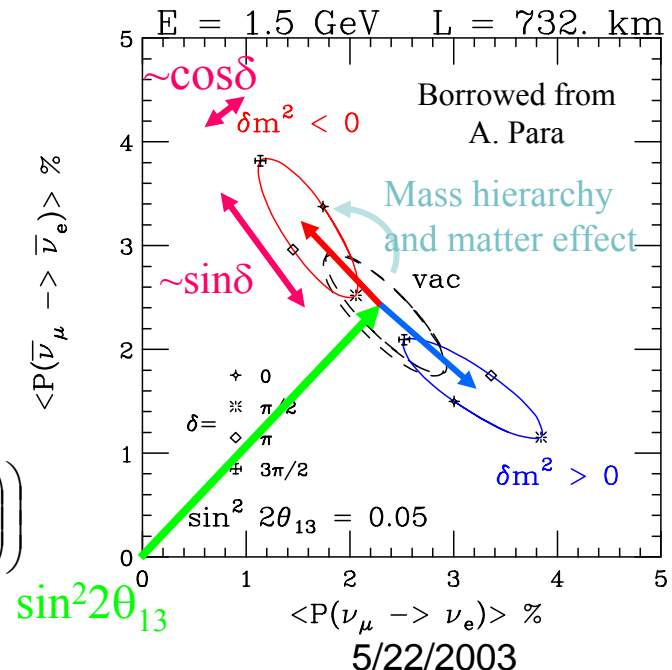   **(JHF-SK and NuMI Off-axis)**

   - Appearance $\nu_\mu \rightarrow \nu_e$ (or $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with separate running)
   - Off-axis to have a monochromatic ν_μ beam
   - Long Baseline (300 – 900 km)
   - Very large detector

$\sin^2 2\theta_{13}$ is not independently measured − parameter degeneracy
(CPV phase δ, matter effects and mass hierarchy)

$$P\left(\nu_\mu \rightarrow \nu_e\right) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) +$$

$$\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \times$$

$$\left(\mp \sin \delta_{CP} \sin^3\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos \delta_{CP} \cos\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \right)$$

Method of Measuring $\sin^2 2\theta_{13}$ (Continued)

2. Measure at a Nuclear Reactor
   (Previous experiments CHOOZ and Palo Verde)

- Baseline ~1 km

- Disappearance $\overline{\nu}_e \to \overline{\nu}_e$

- Use identical near detector to measure reactor flux, spectrum and detector efficiency to cancel most systematics

- Look for small rate deviation from $1/r^2$ in a large reactor signal

- Direct measurement of $\sin^2 \theta_{13}$

$$P(\overline{\nu}_e \to \overline{\nu}_e) = \sin^2 2\theta_{13} \, \sin^2 (1.27 \Delta m_{13}^2 L / E_\nu)$$

Combining measurements from these two methods results in the best sensitivity to $\sin^2 2\theta_{13}$ and δ!

Nuclear Reactors as a Neutrino Source

- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ deriving from the β decay of the neutron-rich fission fragments.

- Each fission liberates about 200 MeV of energy and generates about 6 neutrinos. So for a typical commercial reactor (3 GW thermal energy)

$$3 \text{ GW} \approx 2 \times 10^{21} \text{ MeV/s} \rightarrow 6 \times 10^{20} \; \bar{\nu}_e/\text{s}$$
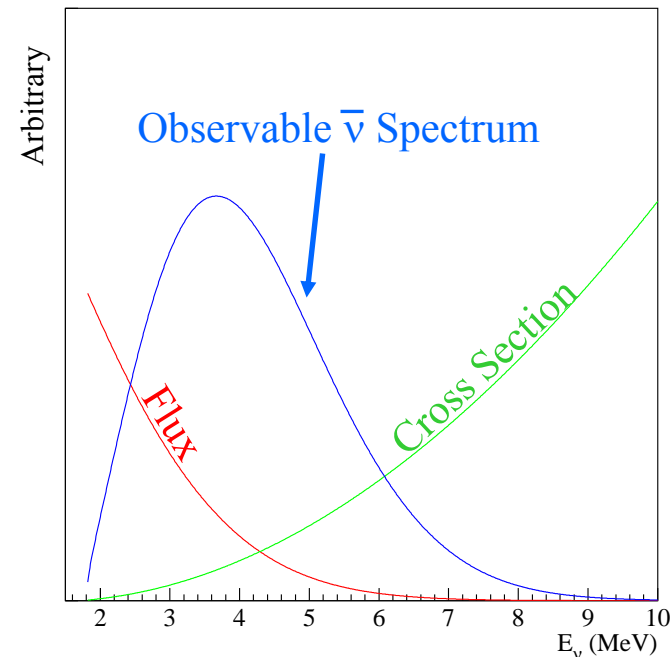
- The observable $\bar{\nu}$ spectrum is the product of the flux and the cross section.

- The reaction process is inverse β decay:

$$\bar{\nu}_e \, p \rightarrow e^+ n$$
$$\hookrightarrow n \; Gd \rightarrow \gamma\text{'s (8 MeV)}$$

~30 μs later
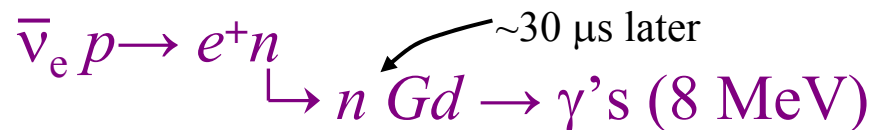
Two part coincident signal

- The spectrum peaks at ~3.7 MeV.

Observable $\bar{\nu}$ Spectrum

Cross Section

Flux

Arbitrary

E_ν (MeV)

CHOOZ

- Homogeneous detector

- 5 ton, Gd loaded, scintillating target

- 300 meters water equiv. shielding

- 2 reactors: 8.5 GW$_{thermal}$

- Used new reactors → reactor off data for background measurement

- Baselines 1115 m and 998 m

- Expected rate of ~25 evts/day (assuming no oscillations)
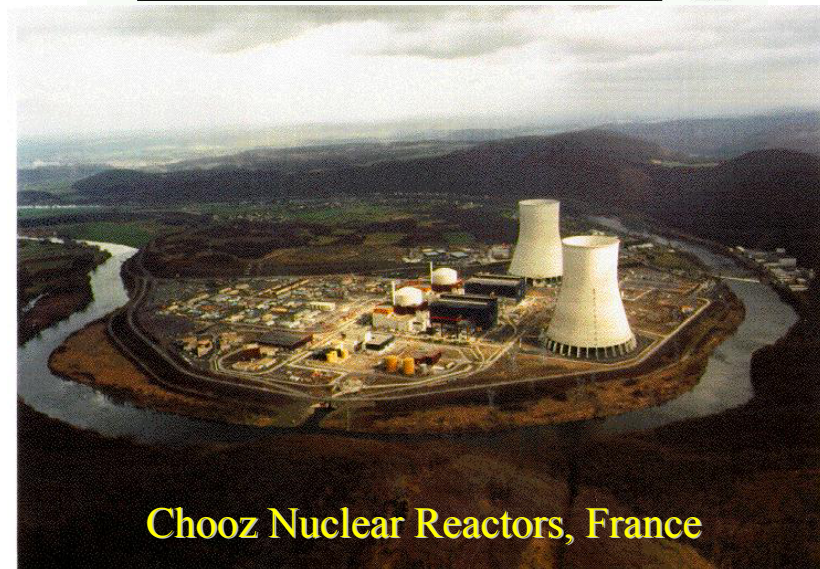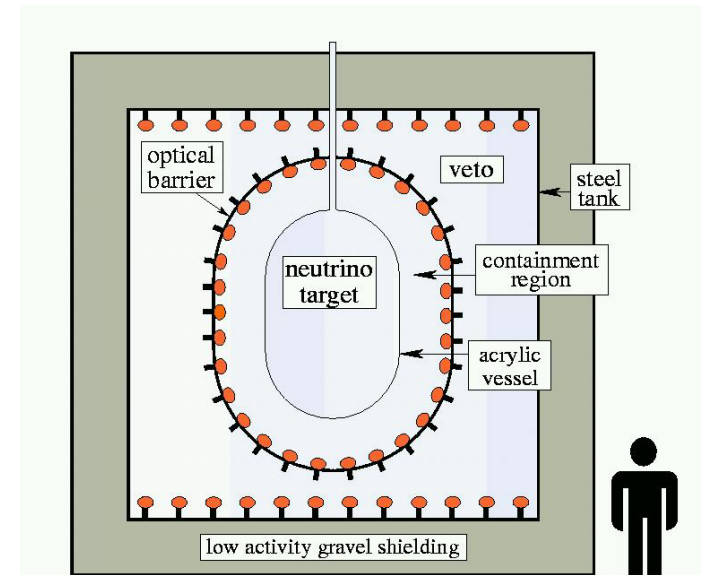
Chooz Nuclear Reactors, France

Palo Verde

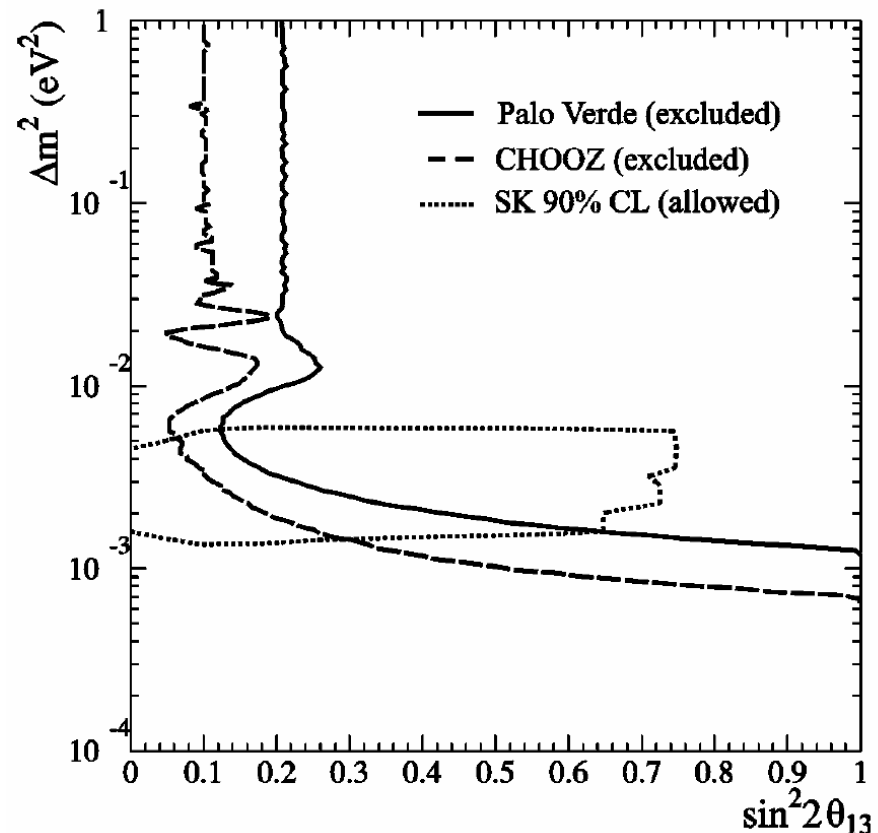Palo Verde Generating Station, AZ
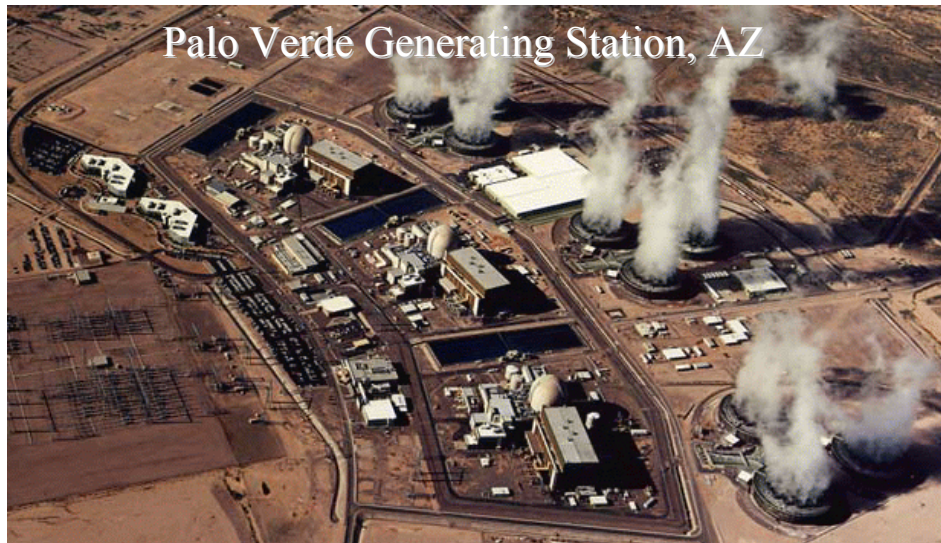
- Segmented detector:
  Better at handling the cosmic rate of a shallow site

- 12 ton, Gd loaded, scintillating target

- 32 mwe shielding

- 3 reactors: 11.6 GW$_{thermal}$

- No reactor off running

- Baselines 890m and 750 m

- Expected rate of ~50 evts/day (assuming no oscillations)

Jonathan Link, Columbia U.   CIPANP2003   5/22/2003
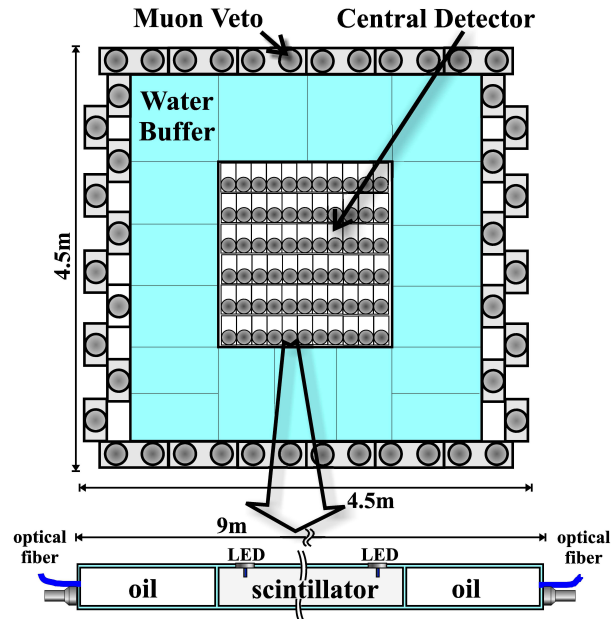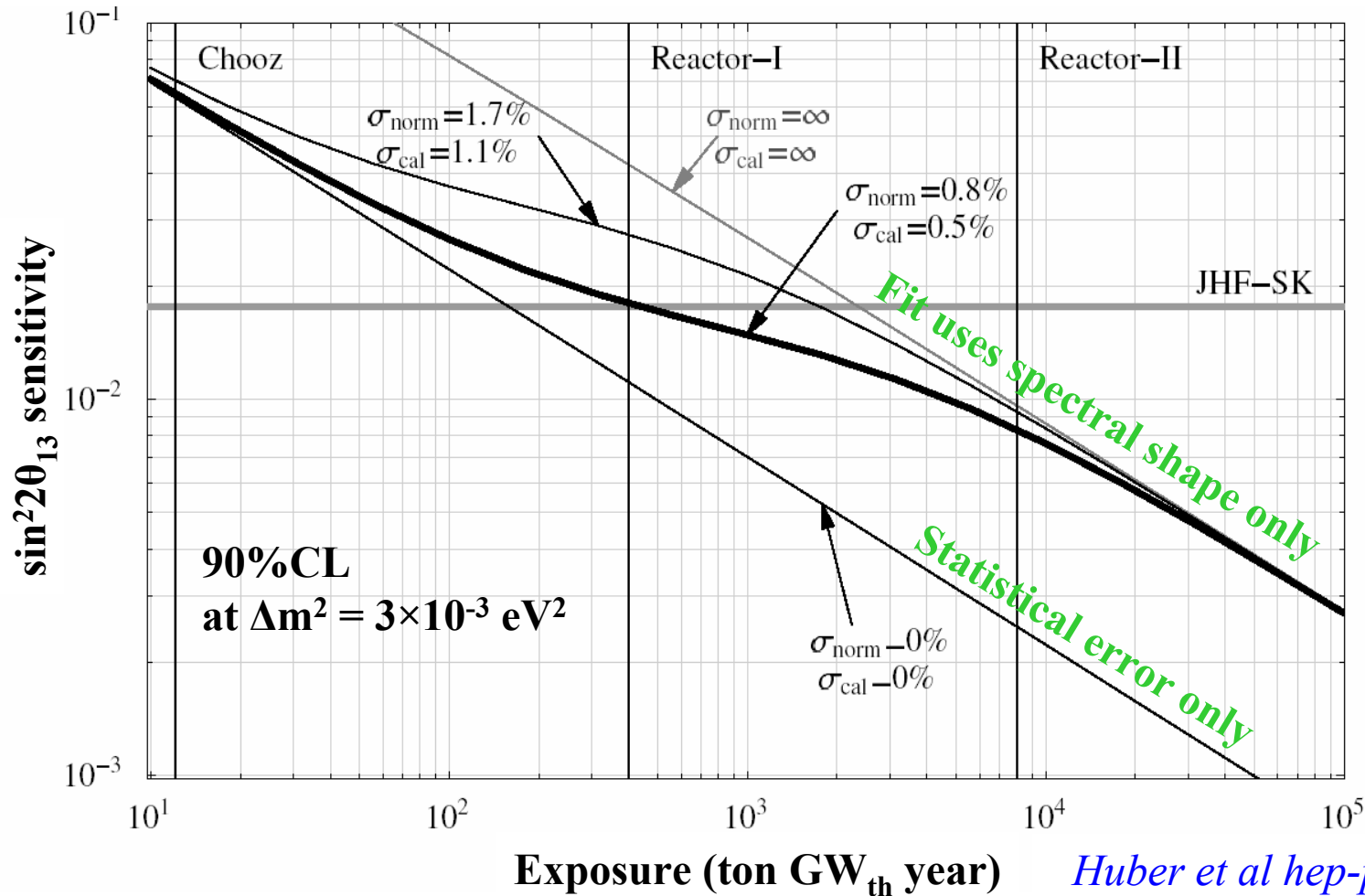
CHOOZ and Palo Verde Results

- Neither experiments found evidence for $\bar{\nu}_e$ oscillation.

- This null result eliminated $\nu_\mu \rightarrow \nu_e$ as the primary mechanism for the Super-K atmospheric deficit.

- $\sin^2 2\theta_{13} < 0.12$ at 90% CL

- Future experiments should try to improve on these limits by at least an order of magnitude.

In other words, a 1% measurement is needed!

Legend:
— Palo Verde (excluded)
- - CHOOZ (excluded)
····· SK 90% CL (allowed)

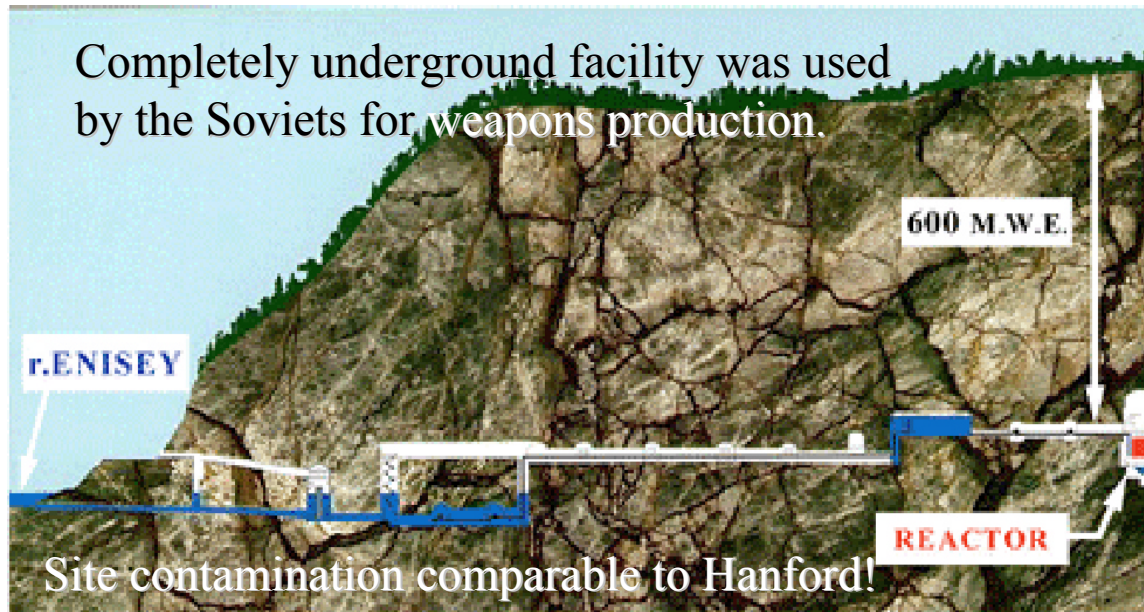Axes: Δm^2 (eV^2) vs $\sin^2 2\theta_{13}$

Sensitivity Reach as a Function of Exposure

Assumes negligible background; σ_{cal} relative near/far energy calibration
σ_{norm} relative near/far flux normalization

Huber et al hep-ph/0303232

Krasnoyarsk, Russia (hep-ex/0211070)

Completely underground facility was used by the Soviets for weapons production.

600 M.W.E.

r.ENISEY
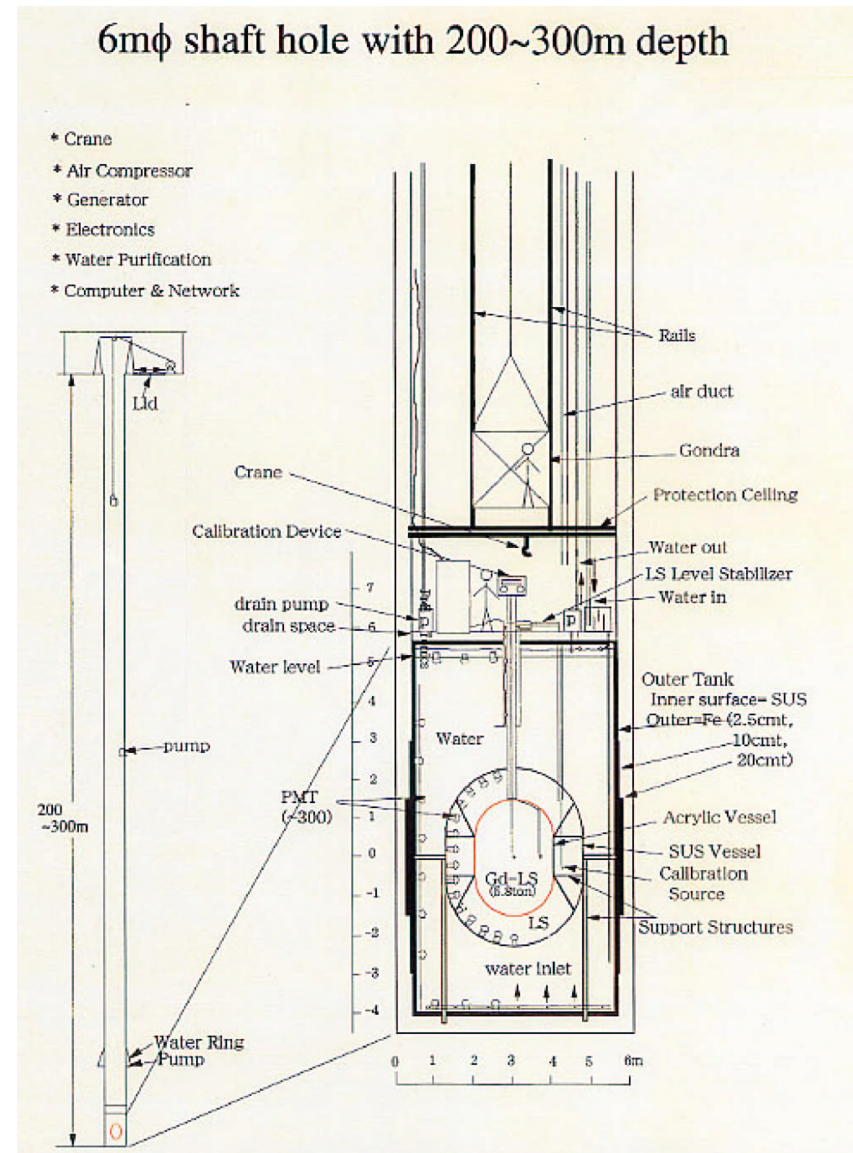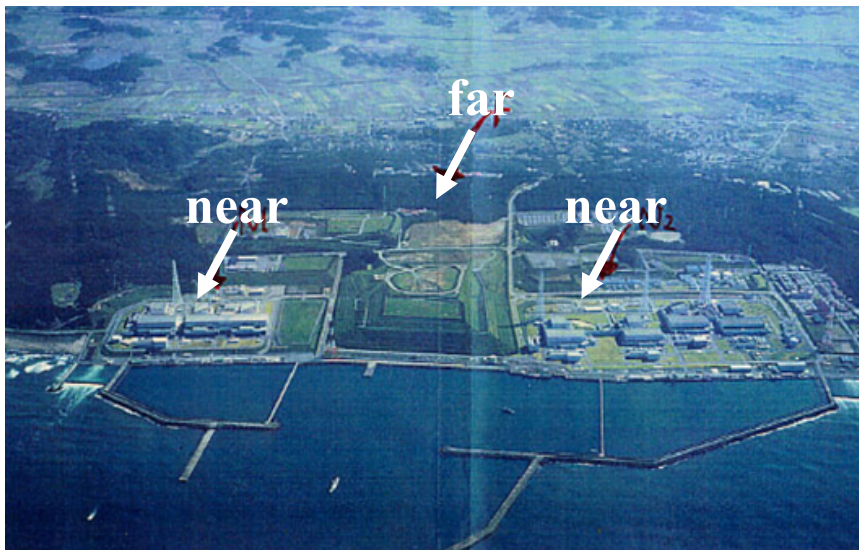
REACTOR

Site contamination comparable to Hanford!

- One ~2 GW reactor

- Two 50 ton detectors

- Near detector at 115 meters

- Far detector at 1000 meters

- About 60 days of reactor off running per year.

- ~100 GW·tons

Reactor $\bar{\nu}_e$ Detector 1   Detector 2

115m

1000m
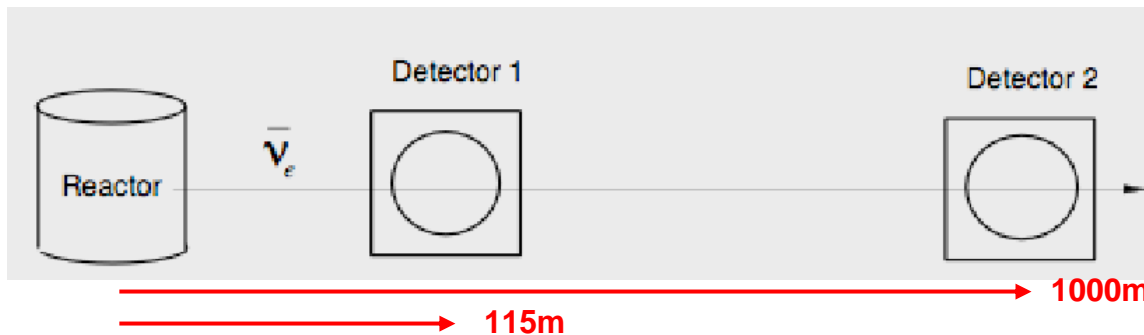
Kashiwazaki, Japan (hep-ph/0211111)

- 7 Reactors, 24 GW$_{thermal}$ (most powerful site in the world)

- Three 5 ton detectors

- Two near detectors at baselines of 300 to 350 meters

- One far detector at ~1700 meters

- 120 GW·tons

far

near$_1$

near$_2$

6mφ shaft hole with 200~300m depth

* Crane
* Air Compressor
* Generator
* Electronics
* Water Purification
* Computer & Network

Possible U.S. Sites

- Most U.S. sites have one or two reactors.

- One and two reactor sites are conceptually easier: only one baseline. (The experiment *can* be done at multi-reactor sites.)

- U.S. two reactor sites are among the best in the world.

- Many U.S. sites have other favorable qualities such as potential for shielding.

The challenge will be getting reactor operators to agree to work with us!

Top 30 U.S. Sites by Power Performance

Reactor Site	State	Cores	Ave GWth	Max GWth
Palo Verde	AZ	3	10570	11552
South Texas Project	TX	2	6864	7600
Braidwood	IL	2	6491	7172
Vogtle	GA	2	6456	7130
Byron	IL	2	6442	7172
Browns Ferry	AL	2	6377	6916
Limerick	PA	2	6365	6916
Peach Bottom	PA	2	6290	6916
Sequoyah	TN	2	6209	6822
Oconee	SC	3	6204	7704
Susquehanna	PA	2	6161	6978
Catawba	SC	2	6116	6822
San Onofre	CA	2	6061	6876
Diablo Canyon	CA	2	6043	6749
Comanche Peak	TX	2	5986	6916
McGuire	NC	2	5880	6822
North Anna	VA	2	5129	5786
St. Lucie	FL	2	4925	5400
Edwin Hatch	GA	2	4901	5526
Arkansas Nuclear	AR	2	4844	5383
Calvert Cliffs	MD	2	4813	5400
Joseph Farley	AL	2	4801	5550
Dresden	IL	2	4779	5914
Brunswick	NC	2	4701	5116
Surry	VA	2	4664	5092
Nine Mile Point	NY	2	4500	5317
Quad Cities	IL	2	4481	5914
Indian Point	NY	2	4467	6096
La Salle	IL	2	4323	6978
Salem	DE	2	4281	6918

What is the Right Way to Make the Measurement?

Start with the Systematics and Work Backwards…

CHOOZ Systematic Errors

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

Near Detector

Identical Near and Far Detectors

Movable Detectors

In the movable detector scenario the far detector spends about 10% of the run at the near location where the relative efficiency of the two detectors is measured head-to-head.

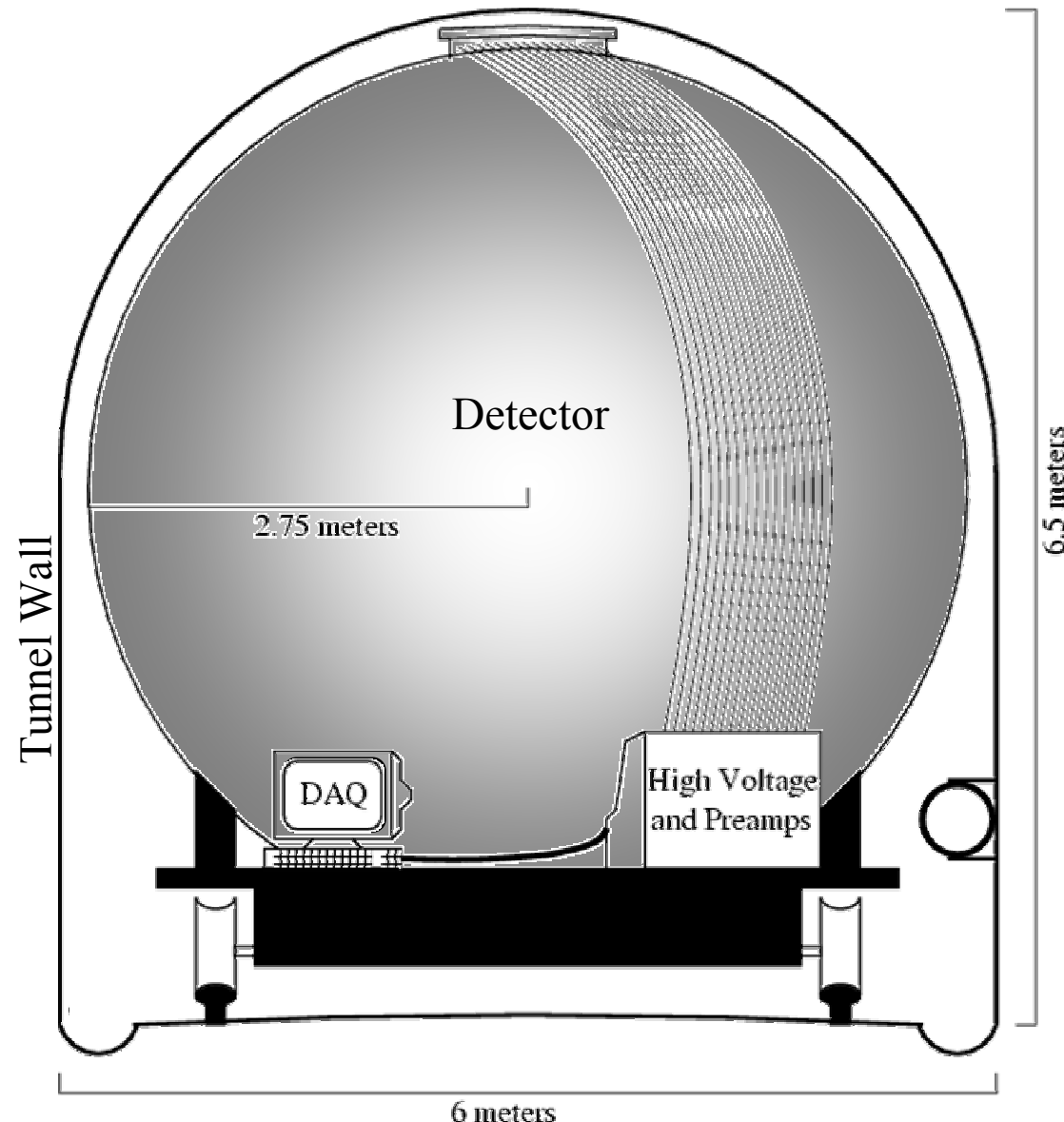Near and far sites need to be connected by a tunnel!

Tunnel Concept Schematic

The detectors must be well underground to reduce the cosmic rate.

Once underground, the best way to move a 100 ton detector is through a level, straight tunnel.
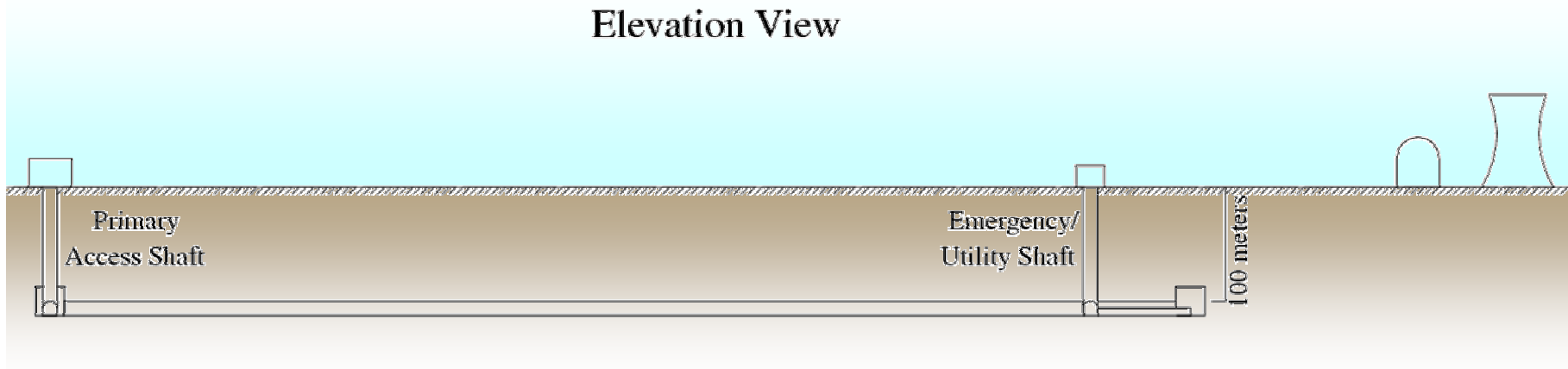
Detector Design

Larger version of CHOOZ (smaller KamLAND)

- Homogenous Volume

- Viewed by PMT's

- Gadolinium Loaded, Liquid Scintillator Target

- Pure Mineral Oil Buffer

In the Movable Scenario

- Rail System for Easy Transport

- Carries Electronics and Front-end DAQ.

Systematic Error from Backgrounds

At sites with more than one reactor there is no reactor off running, so other ways of dealing with backgrounds are needed.
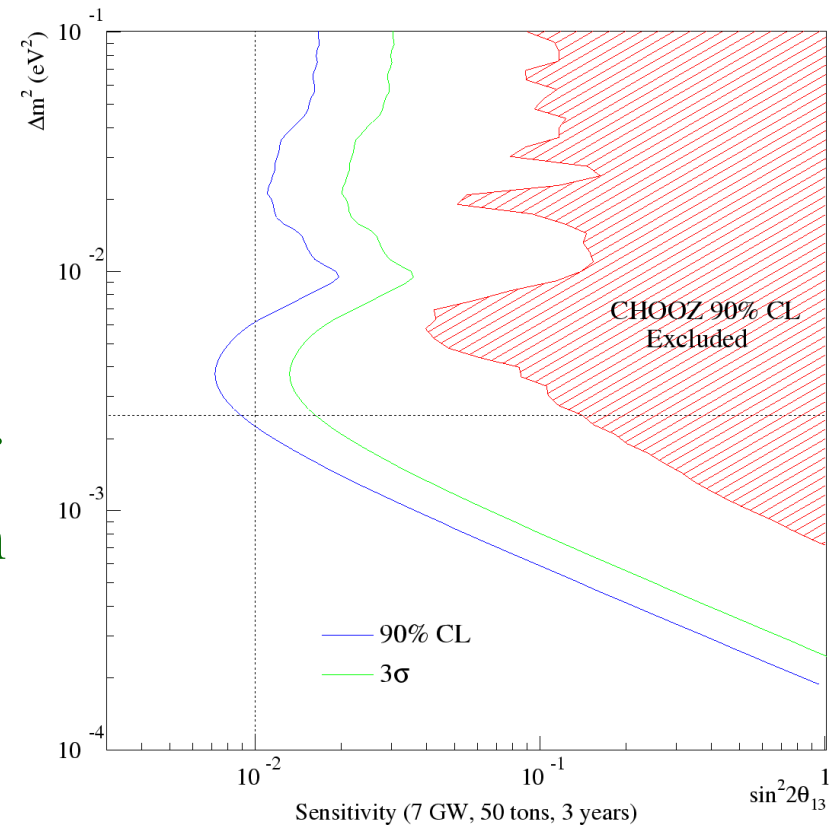
The toughest background comes from fast neutrons created by cosmic μ's. They can mimic the coincidence signal by striking a proton and then capturing.

1. Build it deeper
   (hard to do)

2. Veto μ's and shield neutrons

3. Measure the recoil proton energy and extrapolate into the signal region.
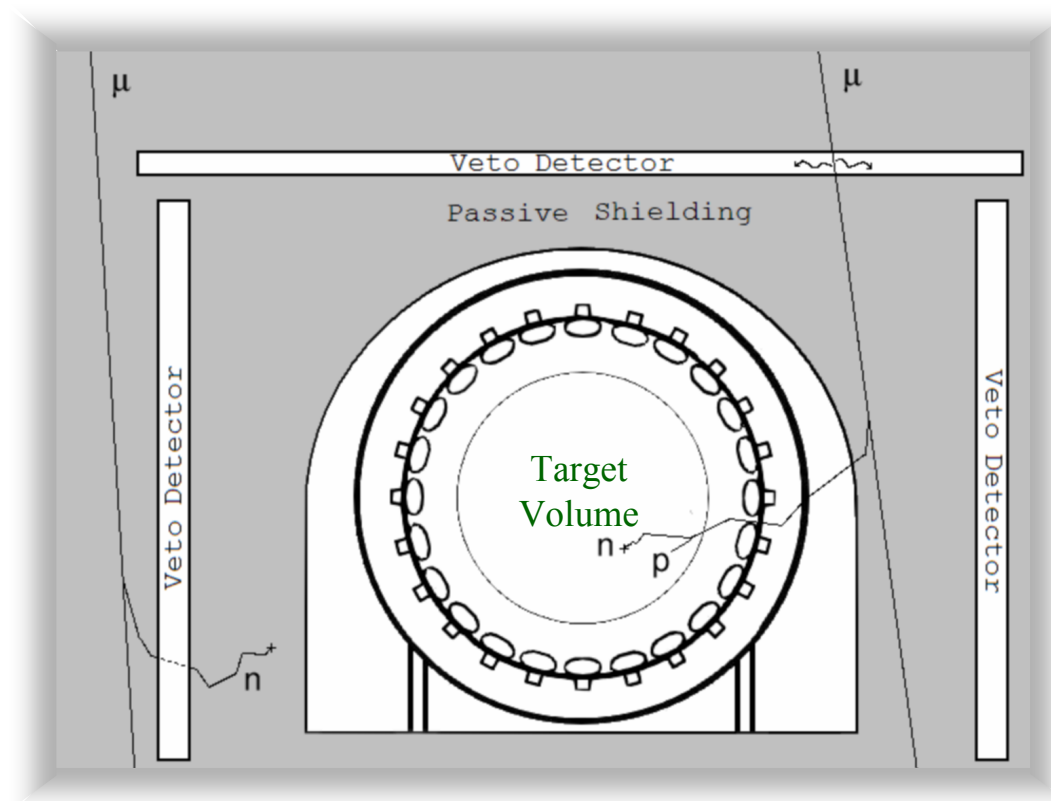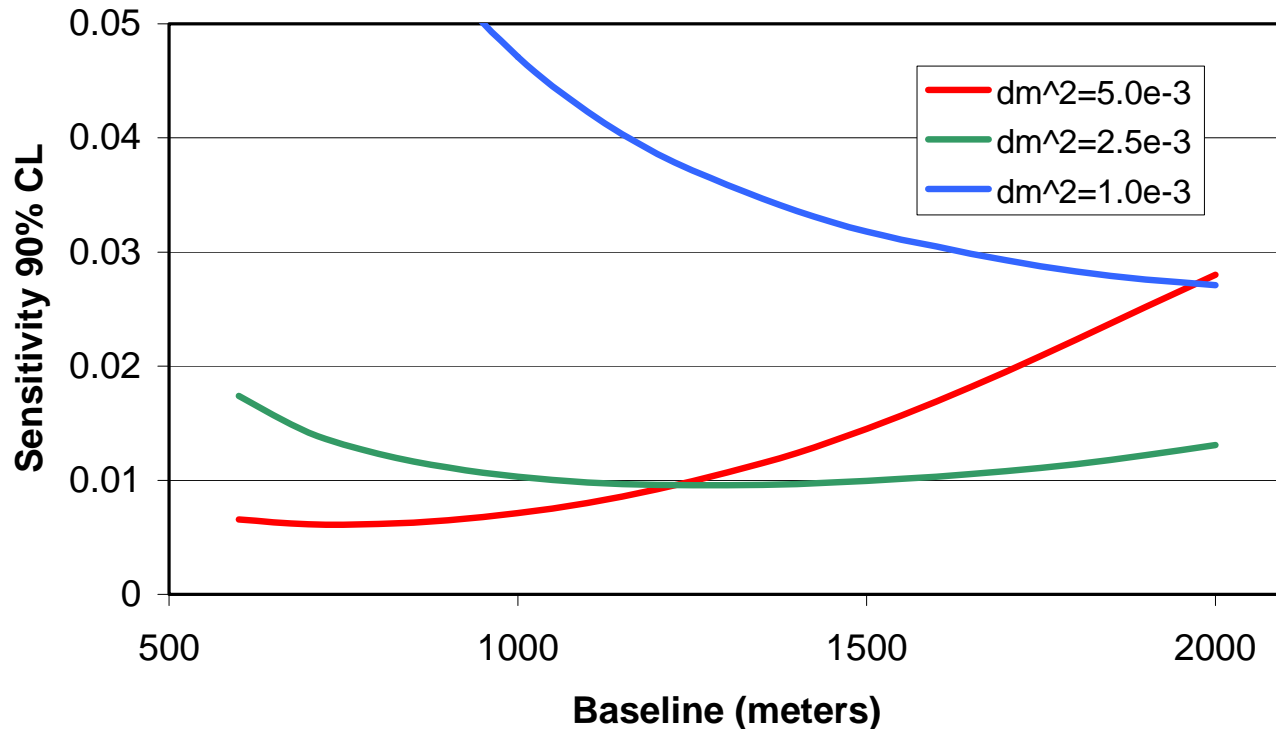
Conclusions and Prospects

• The physics of U_{e3} is interesting and important.

• Reactor ν experiment sensitivities are comparable off-axis and the two methods are complementary.

• An international proto-collaboration has been formed to work towards a proposal by 2005.

• The search for a suitable site in the U.S. is underway.

• Controlling the systematic errors is the key to making this measurement.

• With a 3 year run, the sensitivity in $\sin^2 2\theta_{13}$ could reach 0.01 (90% CL) at $\Delta m^2 = 2.5 \times 10^{-3}$.

CHOOZ 90% CL Excluded

90% CL

3σ

Sensitivity (7 GW, 50 tons, 3 years)

Δm^2 (eV^2)

$\sin^2 2\theta_{13}$

Question Slides

Optimal Baseline

6 GW and 3 Years

One must consider both the location of the oscillation maximum and statistics loss due to $1/r^2$.
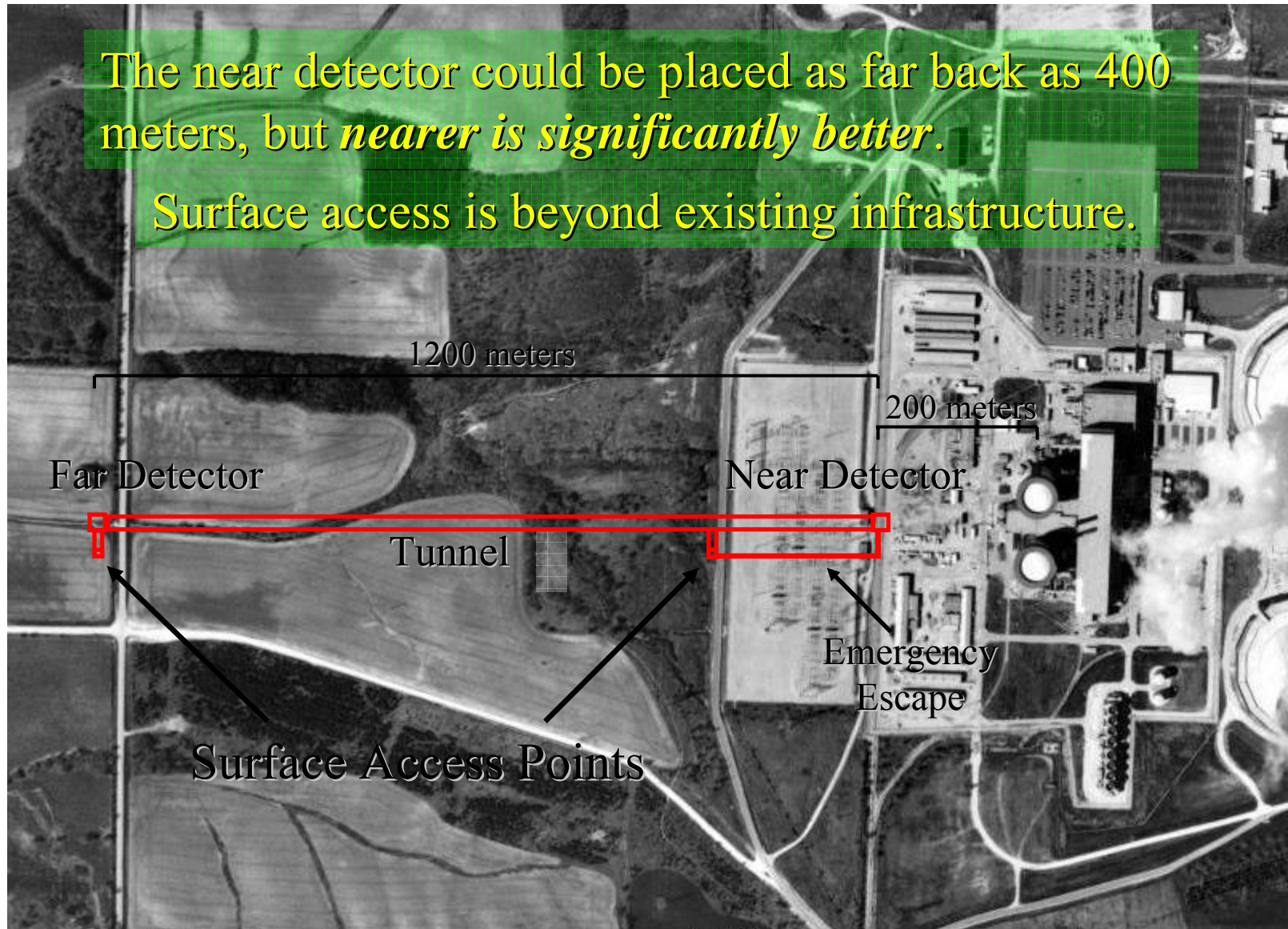
At $\Delta m^2 = 2.5 \times 10^{-3}$ the optimal region is quite wide. In a configuration with a tunnel connecting the two detector sites, one should choose a far baseline that gives the shortest tunnel (~1200 meters).
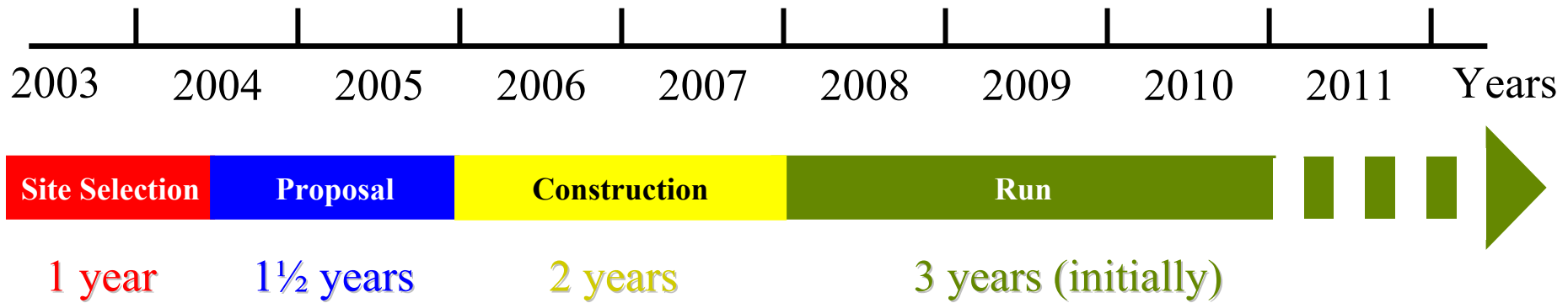
Byron, Illinois

A Possible Site Configuration

The near detector could be placed as far back as 400 meters, but *nearer is significantly better*.

Surface access is beyond existing infrastructure.

1200 meters

200 meters

Far Detector

Near Detector

Tunnel

Emergency Escape

Surface Access Points

Experiment Timeline

| 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Years |

Site Selection	Proposal	Construction	Run
1 year	1½ years	2 years	3 years (initially)

Site Selection: Currently underway.

Proposal Phase: Secure funding from government agencies (NSF and DOE)

Construction Phase: Tunnel construction and detector assembly

Run Phase: Initially planned as a three year run. Results or events may motivate a longer run.

Significant Contributions to the Error

1. Statistics in the far detector

$$\sigma_{stat} = \frac{\sqrt{N_{far} + N_{bg}}}{N_{far}}$$

2. Uncertainty in the relative efficiency of the near and far detector

$$\sigma_{\varepsilon} = \sqrt{\frac{2}{N_{near} f}} \quad \text{(with movable detectors)}$$

where *f* is the fraction of run time used for cross calibration

3. Uncertainty in the background rate in the far detector

$$\sigma_{bg} \cong \frac{\sigma_{bg\ rate} \times N_{bg}}{N_{far}}$$